6.—The Frenchman Bay meteorite

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Abstract

An "iron-shale" encrusted boulder recovered from barren country south of Jurien Bay township, Western Australia, has been recognised as a stony meteorite, deeply weathered. It is a chondrite of spherical type, containing a substantial amount of glass in the chondrules and interstitial to them. X-ray diffraction determination of the olivine shows it to be Fa_{19}, indicating that this is an olivine-bronzite chondrite of Prior's class 2. Details of the chondritic structure are given and an unusual fusion crust pattern is described. There is little or no evidence of recrystallisation.

Details of the find

On 28 September 1964 Mr. R. L. Devitt and Mr. J. H. Turner, both of Perth, noticed a boulder amid limestone outcrops and sand dunes south of Frenchman Bay, some miles from Jurien Bay township, on the west coast of Western Australia. The exact location of the find is shown in Figure 1. It was made at a point 8 miles south-southeast of Wealacutta Pool, Frenchman Bay, and 3 to 4 miles inland from the sea, in an area marked by a small watercourse, the Nambung River, which hereabouts becomes lost amid sand dunes at its seaward termination. The co-ordinates have been estimated as 30° 36′ 30″ South, 115° 10′ East. The terrain is barren and inhospitable, being characterised by numerous limestone pinnacles, arranged like tank traps and rising from bare sand (Figure 2).

Traces of aboriginal habitation were noted by the finders near the site of the find, and, since aboriginals are known to cherish meteorites (especially australites) as "magic stones", human transport from a site of fall elsewhere cannot be entirely discounted (cf. the numerous meteorite recoveries in American Indian country where the same sort of doubt exists: Nininger 1952 p.7-8). Because of the size of this meteorite, however, such a happening seems unlikely and we may safely assume that this was the actual site of the fall.

Figure 2.—View of the site of the find, looking seawards.

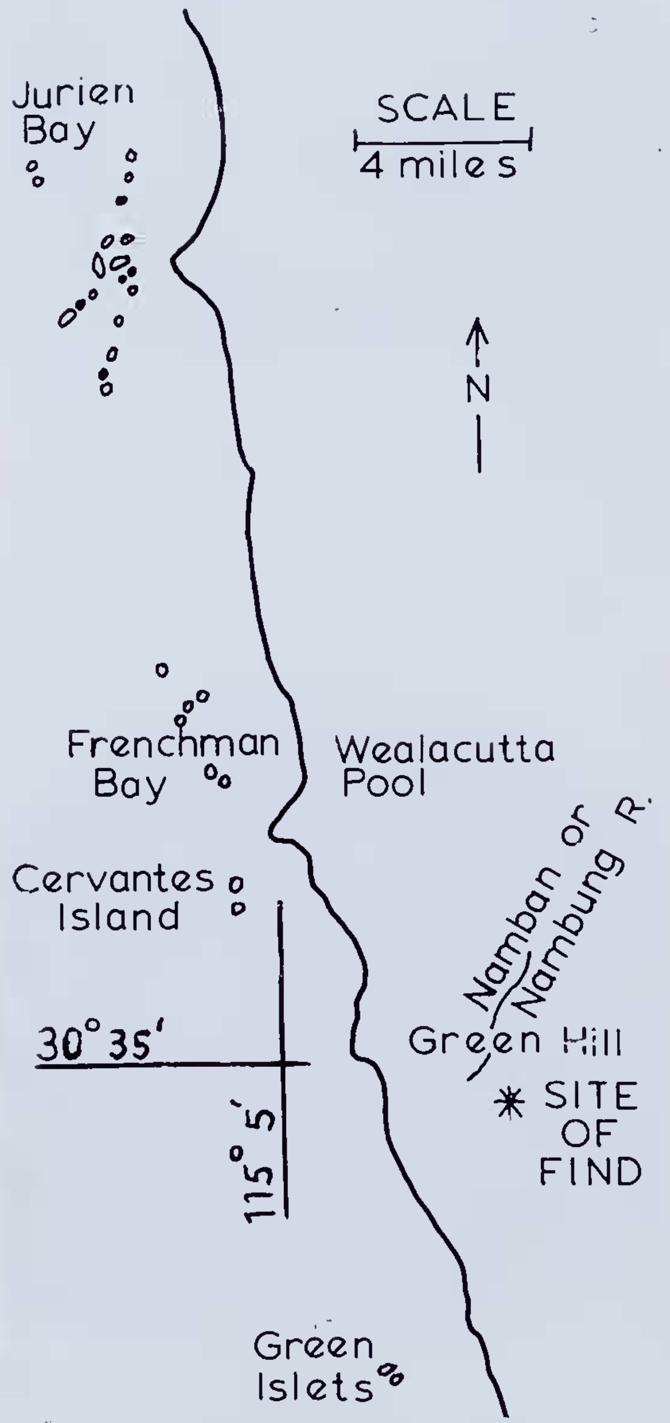

Figure 1.—Sketch map showing the location of the find.

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The finders transported the boulder to Perth, where the writer was asked to examine it. Unpromising as it appeared at first sight with its flaky coating of "iron-shale", its high density, the semblance of a facetted surface, and a patch of fusion crust at the narrow termination, combined with Mr. Devitt's assertion that it was exotic—"a foreigner"—led to a suspicion that it might be a highly weathered meteoritic stone. This suspicion became a certainty with the first cut of the diamond saw, for a greenish-grey core punctuated by spherical chondrules appeared. Microscopic examination confirmed this and also the tentative identification of a black patch on the narrow termination as fusion crust.

Physical properties and external features

The mass is a single, flattened, crudely pear-shaped body, possessed of one broad, blunt termination, and one narrower, rounded termination (Figures 3 and 4). The total weight before cutting was 19.4 lbs (8.8 kg) and the maximum dimensions were 10 x $7\frac{3}{4}$ x $4\frac{1}{4}$ inches. Up to $\frac{3}{4}$-inch of oxidised, scaly crust, an "iron-shale" composed largely of limonite, was revealed on sectioning the mass (Figures 3 and 4). The transition to comparatively fresh core material is somewhat abrupt. The limonitic crust is cracked and flakes off readily, but the core material is compact and cohesive.

The specific gravity of core material, measured using carbon tetrachloride, was found to be 3.20, considerably lower than the average for the common types of chondrites (3.51 for olivine-hypersthene chondrites and 3.6-3.8 for unweathered olivine-bronzite chondrites; Mason 1962), but this anomaly is not significant in view of the decomposed state of the nickel-iron/troilite fraction.

Fusion crust is only preserved in an oval patch, measuring $2\frac{1}{2}$ x 2 inches diameter and situated in a hollow area at the narrow termination of the mass (Figures 3 and 5). It is dull, black and of variable thickness, locally exceeding 1 mm. The rough character and thickening suggests that it may well represent a posterior ablation surface in atmospheric flight, but there is no other indication of flight orientation (cf. McCall and Jeffery 1964 pp.36-38).

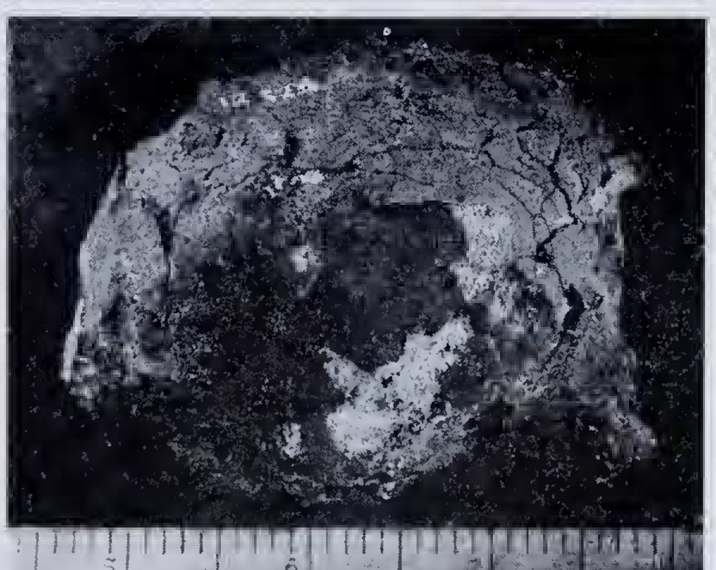

Figure 5.—The section cut off the narrow termination of the mass, showing caliche encrustation (white) and an oval patch of fusion crust (dark), on an otherwise monotonous "iron-shale" crust.

Figure 4.—Views of the single mass after cutting off the pointed termination with the diamond saw. The rough, cracked ferruginous crust is evident in all three photographs, and the first two show the facetted form of the mass. The lowest photograph shows the dark, fresh core, speckled with spherical chondrules, within this thick crust. The mass shown is 8 inches long, and the width of the cut face is 5 inches.

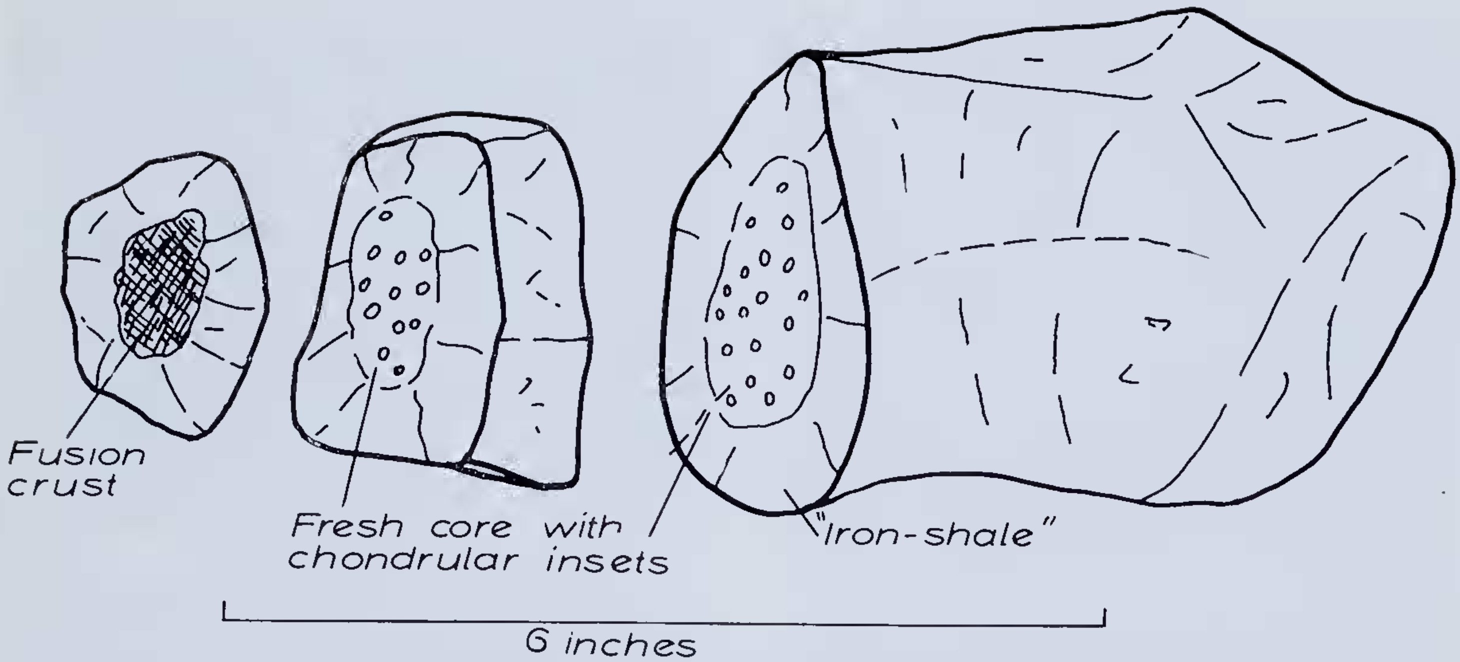

Figure 3.—Drawing of the entire single mass after cutting through the narrow terminatino with the diamond saw. Facetted form, terminal fusion crust coated area, and relation of fresh core materil to "iron shale" crust are shown.

Microscopic detail

Fusion crust

This is best seen under a binocular microscope using low magnification and oblique reflected light. The texture is mamillated in the manner of a blackberry fruit—it seems to be the type called "warty" by Krinov (1961 pp.270-272). The warty protuberances are clustered sporadically on a rough surfaced layer of compact, black glass about half a millimetre thick (Figure 6), and produce an irregular thickening of the crust. They are, perhaps, best described as mamillations. Also projecting from the compact crust, at all angles, are flat hexagonal plates up to 1 millimetre diameter. These show concentric lines on their side surfaces, parallel to the edge of the hexagon. They are well formed crystals of some mineral. There are two possobilities, nickel-iron (Krinov 1961 pp.273-4) or troilite. The former seems unlikely and it is more probable that these are troilite plates, recrystallised by the heat of ablation. The crystal form appears to be that of troilite. These hexagons are overlain by the mamillations, giving a shiny lustre instead of a dull grey surface, and it is certain that the mamillations were superimposed on the hexagons.

Comparison with the fusion crust of another chondrite (Woolgorong; McCall and Jeffery 1964) under a single field of view of the binocular microscope leaves no doubt that this is a relic of the fusion crust, not a secondarily derived gocthite surface, due to terrestrial agencies. The crust was studied in crushed particle mounts under transmitted light and was found to include brown, isotropic glass containing minute vermiform inclusion, and also radial clusters of anisotropic fibres. The latter could also be recognised under oblique reflected light in a large, broken mamillation, and so cannot be dismissed as artifacts due to crushing. They show straight extinction and are interpreted as due to shock during atmospheric flight or on impact, and having originally been isotropic glass. Iridescence is locally evident on the mamillated surface and could also be due to shock.

Krinov (1961 p.270-272) explains warty protuberances on fusion crust as due to spattering: material ablated free from the tail end is supposed to catch up with the meteorite as it decelerates to the point at which all cosmic velocity is lost. The superimposition of the mamillations on the hexagon does suggest a late spattering effect, but it seems possible that a less

Figure 6.—Drawing of the fusion crust made under oblique reflected light with a binocular microscope. Microbotryoids are superimposed on hexagonal plates. The diameter is 2.5 mm.

complicated explanation could be found. No record of a fusion crust of this exact type could be found in the literature, though it is possible that such a texture has been described in some text not familiar to the writer.

Core material

The texture of the relatively fresh material of the core shows up well under the binocular microscope using oblique reflected light. The chondrules are seen to be predominantly spherical and the majority are complete, though there are some broken fragments indicating limited brecciation. Some complete chondrules appear distorted without actual fragmentation. Narrow cracks, many of them infilled with iron oxides, form a close network, some being micro-faults which displace oppsing halves of individual chondrules relative to one another. It seems likely that most of these cracks were initiated within the parent body before disruption, long before the meteorite came into contact with the Earth's atmosphere. The reason for believing this stems from the recognition of many troilite infilled cracks within fresher stony meteorites (McCall and Jeffery 1964 p.38-9; McCall 1966). From the amount of iron oxide in the cracks traversing this stone it is assumed that they have contained troilite. It does not seem likely that troilite could fuse, penetrate cracks through the meteorite and recrystallize again under the influence of ablation, but in view of the evidence of possibly recrystallization of troilite at the fusion crust surface this cannot be entirely discounted. Some cracks may be due to shock on impact and have suffered purely terrestrial infilling by ferruginous material. There is little trace of troilite now preserved, though traces of kamacite are still evident, and precise interpretation of the cracks is difficult. There is no trace of a directed texture, comprising troilite and nickel-iron flecks as in the Dalgety Downs meteorite (McCall 1966).

Thin section study under transmitted light also reveals the spherical texture of the chondrite (Figure 7 A and B). The chondrules are set in a sparse, opaque base which has probably been a ferruginous glass interspersed with kamacite and troilite grains. The chondrules themselves are largely iron-free, but some show dark, ferruginous haloes. The matrix contains fragments of the minerals present in the chondrules, probably material derived from disrupted chondrules and indicating that, in spite of the perfectly spherical form of most of the chondrules, the texture shows some reflection of penetrative brecciation at an early stage in the history of the meteorite, in addition to localised rupture by microfaulting, part or all of which may be late.

There is a wide variety of chondrule types. Monosomatic, barred olivine chondrules are evident, though scarce (Figue 9A). Polysomatic chondrules, including excentric fan (Figure 9A), finely grated and microporphyritic types (Figure 8) predominate: some of the latter show vitrophyric character, having an interstitial matrix of clear, clove-brown glass separating the olivine crystals, some of which show euhedral, gable-ended form (Figure 8A). Of particular interest

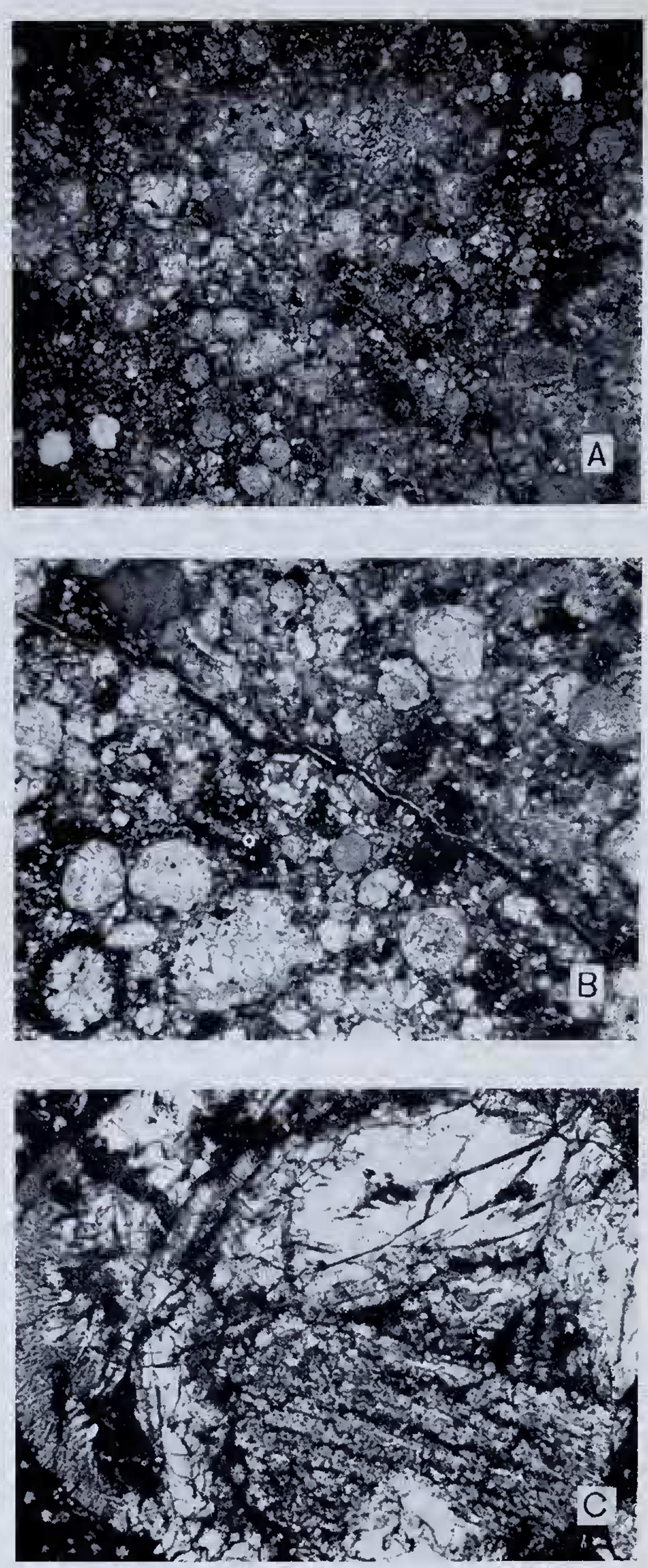

Figure 7. A.—"Spherical" chondritic structure (x6.5, plane polarised light). B.—Part of the same, enlarged to show the broken nature of some chrondrules, the dark ferruginous selvedge of others, and the fine, iron oxide filled fracture lines (x16, plane polarised light). C.—A large composite chrondrule, containing olivine in euhedral form (upper, right) and barred form (lower, right), orthopyroxene (extreme left) and glass (interstitial, dark). Barred, (lower right), microporphyritic (upper right) and excentric fan (extreme left) textures provide a textural inhomogeneity, in addition to the mineralogical inhomogeneity. (x40, plane polarised light).

are the composite chondrules: these have a two-fold composite character, being composed of more than one mineral and evincing more than one of the textural types of chondrules, first described by Tschermak (1885). The largest chondrule in the two thin sections prepared contains olivine, hypersthene and interstitial glass, and, in addition, three distinct textural types are seen in sectors which together comprise the chondrule—microporphyritic, barred, and fan textures (Figure 7C).

Mineralogy

Olivine occurs as euhedral crystals, subhedral grains and within grated and barred chondrules. Its moderate birefringence contrasts with the lower birefringence of the orthopyroxene. It has been determined by X-ray diffraction as $(Mg_{.81}\ Fe_{.19})_2\ SiO_4$.

Orthopyroxene is the only other silicate mineral identified, and is the most abundant. It is a non-pleochroic variety, and occurs mainly in fibrous aggregates, though there are also some broad, elongated crystals present. In some fan chondrules the fibres are so fine that the chondrules are cryptocrystalline (Figure 9A) but brush polarisation with straight extinction is apparent under high magnification, showing that crystalline material predominates, though glass may also be present. Physical separation of grains and more refined methods of study would be needed to determine both $MgSiO_3/FeSiO_3$ ratio and alumina content with a high degree of accuracy, but, in fact, the olivine determination of Fa_{19} gives an indication of the composition of the pyroxene.

A lamellar pyroxene (cf. Tschermak 1885 Fig.58) is present in accessory quantity (Figure 9 B). Such lamellar pyroxenes show consistently low birefringence (first order greys) and high extinction angles, ranging up to 40 degrees. The lamellae may appear indistinct or well defined as in the grain illustrated (Figure 9 B). The consistently low birefringence and high optic angle observed are atypical of pigeonite. These grains seem to be orthopyroxene with exsolution lamellae. Such lamellae may be due to one of two causes (Deer, Howie and Zussman 1963 pp.15-26): gliding under stress, or exsolution of a calcic clinopyroxene in very narrow bands (Schiller inclusions). It is known that the former mechanism does apply to some meteorites (e.g. Shallowater achondrite; Deer, Howie and Zussman 1963 p.32). Some site is nevertheless required for the normative calcium silicate always revealed on chemical analysis of chondrites (it has always been the custom to put such calcium silicate in bronzite in meteorite norm calculations—see comment, McCall and Jeffery 1964 p.41) and the existence of cryptic Schiller inclusions has always seemed to resolve this anomaly in a most satisfactory manner. Similar lamellar orthopyroxenes are evident in the Narctha (McCall and de Laeter 1965) and Dalgety Downs (McCall 1966) chondritic stones and it is clear that they are by no means uncommon in olivine-bronzite and olivine-hypersthene chondrites. B. H. Mason (written communication) considers this lamellar-twinned pyroxene to be pigeonite (*sensu lato*). Recent

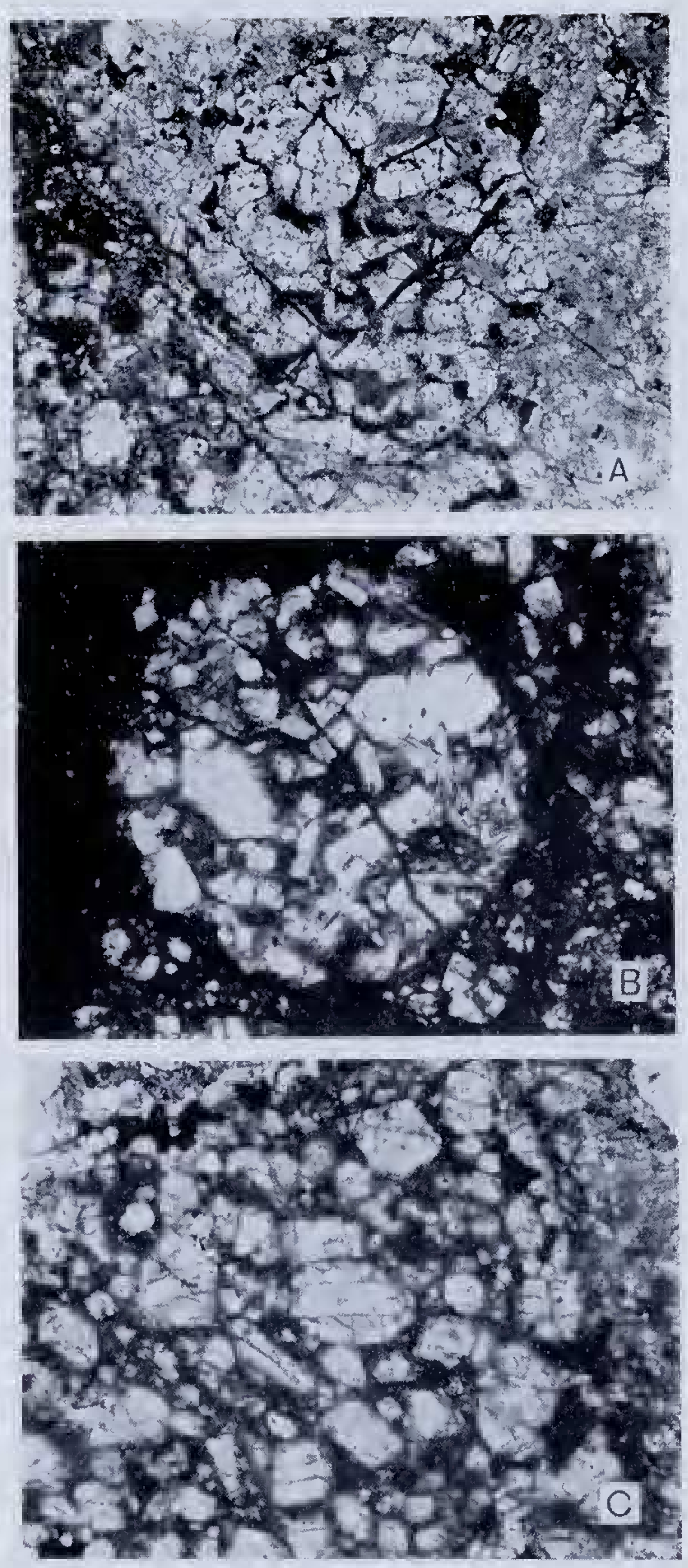

Figure 8. A.—Microporphyritic chrondrule containing subhedral olivine crystals (but showing gable terminations) in a base of devitrified glass; the fragmental inter-chrondrular matrix also shows up well in this photograph (x40, plane polarised light). B.—A similar microporphyritic olivine chrondrule showing euhedral olivine crystals set in a translucent glass base (grey), istotropic under crossed nicols. The peripheral matrix material surrounding this chondrule seems to be of amorphous material, probably iron oxide stained glass (x40, plane polarised light). C.—A similar vitrophyric chondrule shown under even higher magnification, at which the interstitial material still shows no resolution into discrete grains. It is translucent, though staining makes it appear mottled grey in the photograph. Under crossed nicols it is fully isotropic (x65, plane polarised light).

X-ray diffraction studies of pyroxene concentrates from chondrites show it to be present in appreciable amounts in practically all chondrites. It had been previously overlooked in optical studies of refractive indices because of the practice of selecting clear, coarsely crystallised orthopyroxene grains and neglecting the turbid, finely-crystallised clinopyroxene grains. Much of the normative plagioclase in chondrites may actually be combined in this pigeonitic clinopyroxene.

Plagioclase could not be identified and it must be assumed that the plagioclase (oligoclase) component always present in chondrite norms, is here locked up in the glass fraction.

Glass. There is true glass evident in the interstices of some of the microporphyritic olivine chondrules (which are more correctly termed microvitrophyric) (Figure 7, B and C). It is clove-brown coloured and translucent, appearing completely isotropic, though in other chondrules the interstitial glass appears slightly turbid, and largely anisotropic, indicating some degree of devitrification (Figure 7 A). B. H. Mason (written communication) now recognises that interstitial glass such as this is a fairly common feature of chondrules in highly chondritic meteorites. Metamorphism and recrystallisation which has affected many chondrites results in disappearance of this glass by devitrification and crystallisation. Microprobe analyses of such glass shows that its composition resembles that of oligoclase, indicating that it is probably the occult feldspar in these glass-containing chondrites. He further suspects that solid state recrystallisation (metamorphism) produces the orthopyroxene from the clinopyroxene, with the plagioclase separating from the Ca, Na, Al in the clinopyroxene. Such a process would explain the prominence of lamellar-twinned pyroxene, and paucity of oliclase in these highly chondritic chondrites, devoid of evidence of metamorphism, and the abundant recrystallised plagioclase and paucity of clinopyroxene in highly recrystallised chondrites such as Woolgorong (McCall and Jeffery 1964).

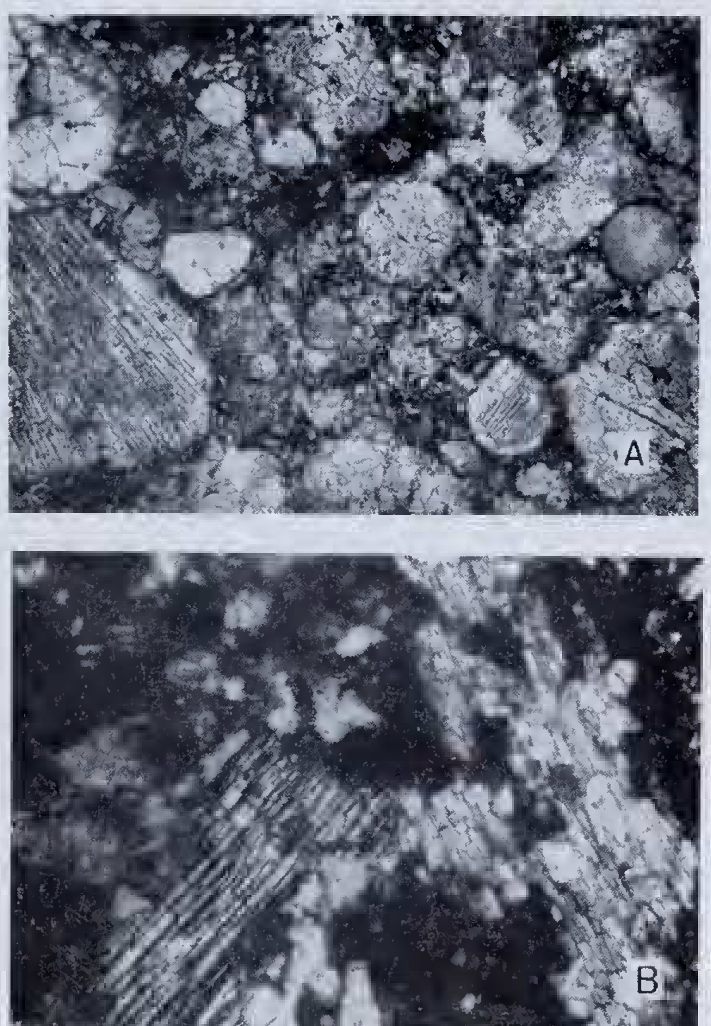

Figure 9. A.—A monosomatic barred olivine chondrule with an annular rim is evident (lower right). The more common excentric fan chondrules are seen (left and middle, right). The former is coarsely crystalline and not preserved in its entirety, being broken: the latter is ultrafinely fibrous (x40, plane polarised light). B.—Lamellar pyroxene in a position of extinction of the exsolution lamellae (cross hairs parallel to margins of photograph) (x105, crossed nicols).

Mode. An approximate mode for the fresh meteorite has been visually estimated:—

	%
Olivine	35
Orthopyroxene (including lamellar grains)	45
Nickel-iron (kamacite) plus troilite	15
Glass	5

X-ray Diffraction Studies

Olivine. Using the method of Yoder and Sahama (1957), olivine from this meteorite was identified as Fa_{19} (analyst B. H. Mason). This provides the clearest evidence that it is an olivine-bronzite chondrite of Prior's class 2 (Mason 1963). It is, indeed, very similar to the Selma meteorite, figured by Mason. (1962 p.90), but reveals slightly less interstitial material and a slightly higher degree of brecciation. As in the Selma meteorite, advanced oxidation under atmospheric conditions precludes full chemical analysis.

Orthopyroxene. The inference may be drawn that the orthopyroxene is about Fs_{18} since orthopyroxenes take up slightly less of the iron slicate molecule than the olivines.

Glass. The microbotryoids were crushed and an X-ray diffraction photograph obtained from the powder. This was carried out in order to establish the nature of the anisotropic, fibrous material in the fusion crust. The picture obtained suggests that the material is a mixture of amorphous material and γ-ferric oxide (maghemite).

Conclusions

This new find poses some interesting problems:—

(a) The fusion crust shows hexagonal plates. This feature does not appear to be recorded in the literature, and requires explanation.

(b) The largest of the contained chondrules, with their two-fold composite character present a problem of mode of formation, one that must be answered before any hypothesis of chondrule formation can be regarded as a reasonable theory. It may be naïve for the geologist to ask this question, but can such patterns within chondrules be reasonably equated with Wood's hypothesis (1963 p.382) of condensation within the gaseous nebula prior to the formation of the solar system? Could such a complexity develop from matter in a primordial state, in which the necessary degree of heterogeneity is surely not to be expected?

(c) The existence of clear glass in some chondrules cannot be denied. Such an occurrence has some relevance to studies of devitrification, so important to vulcanologists. An occurrence of glass of Precambrian age in terrestrial rocks has been reported (975 m.y; Philpotts and Miller 1963) suggesting that something more than mere passage of time is required for devitrification to occur. The great age inferred for chondrule formation from isotropic evidence combined with the presence of true glass suggests that meteorites are insulated from the agencies, which, with the passage of time, almost inevitably act to devitrify terrestrial glasses.

Of more local interest is the fact that this discovery represents the first one made close to the West Australian coast. It was noted during the compilation of a catalogue of meteorite occurrences in this State (McCall and de Laeter 1965) that there was a complete blank in the coastal areas, contrasting with the numerous discoveries inland. The discovery of this deeply weathered stone supports the belief that sea air, being particularly destructive to nickel-iron masses, militates against any long term preservation of stony meteorites or irons in the coastal areas, while stony masses may be preserved for centuries in the arid interior of the State. In the coastal finds deep weathering cannot be taken as indicative of a long terrestrial history—the lack of any record of a fireball and related phenomena in the district is of no significance in view of the low population density. The Frenchman Bay meteorite may be a comparatively recent fall, not more than a few years ago.

Acknowledgements

To the acute observation and interest displayed by Mr R. L. Devitt and Mr J. H. Turner we owe this discovery, and their generosity in presenting the meteorite to the Western Australian Museum must be acknowledged. Dr. B. H. Mason assisted the writer with X-ray diffraction determination of the olivine and Mr J. R. de Laeter investigated the fusion crust using similar techniques. Technical work in support of this investigation was carried out by Mr W. Smeed and Mr K. C. Hughes (photographer). The line drawings used in Figures 1 and 3 were drafted by Miss Rosemary Hunt and the drawing of the fusion crust used in Figure 6 was made by Miss Robin Peers.

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